The non-linear development of basic attentional functions and attentional collaborations in primary school children examined with the High Reliability-Composite Attention Test

Running title: Reliable developmental trajectories of attention

Abstract: The development of attentional functions is a fundamental issue of human cognitive development, but the available evidence for its developmental trajectory is inconsistent due to the diversity and low reliability of measurement paradigms. The study examined the development of attentional functions and attentional collaborations in 281 Chinese primary school children (109 girls, 5.98-13.24 years old) using the self-designed High Reliability-Composite Attention Test. Results showed that the executive control continued to develop prior to the age of 10. It further contributed to the linear development of attentional collaborations. Each of these scores exhibited a split-half reliability exceeding 0.82. Therefore, we effectively demonstrated a mechanism for attentional development that revolves around executive control.

KEYWORDS: attentional development, High Reliability-Composite Attention Test, attentional collaboration, attentional interaction, gender difference.

Research Highlights

- We combine a steady-state design with a block design, revise the attention network test and propose a new measurement paradigm.
- This revision allows for more valid and reliable measurements of attentional functions, with reliability results exceeding 0.8, which can be used as a reliable instrument for attention measurement.
- The non-orthogonal computational method allowed us to assess for the first time the developmental trajectory of collaborations and interactions between attentional functions.
- The study sheds new light on the developmental mechanisms of attention by emphasizing the pivotal role of executive control and its relationship to other attention functions.

1 INTRODUCTION

Attention is a pivotal cognitive function that directs limited cognitive resources to information most relevant for behavior, shaping what we perceive, think, and do (Bridewell & Bello, 2016; Chun et al., 2011). It has attracted human interest for over 3000 years (Almeida et al., 2021). To date, there is still no extensively accepted unified theory of attention, due to its complexity and multifaceted nature (Wyble et al., 2020). In a highly impact paper, Posner and Petersen divided attention into three networks: alerting, orienting, and executive control (Posner & Petersen, 1990). The alerting network refers to achieving and maintaining a state of high vigilance; the orienting network shifts the focus of attention toward specific inputs; while the executive control network identifies and resolves conflicts that arise from competing mental processes (Xuan et al., 2016). The three networks are linked with distinct neural circuits and neurotransmitter systems, respectively (Xuan et al., 2016). The triple-network theory has undergone rigorous analysis and is one of the most extensively investigated attention theories in laboratory, developmental, and clinical contexts (Petersen & Posner, 2012).

Attention is one of the most important cognitive abilities for adaptive behavior during childhood and for meeting daily demands both in school and in social interactions (Lewis et al., 2017; Posner & Rothbart, 2007). In addition, as children enter school age, the impact of attentional disorders, such as Attention-deficit/Hyperactivity Disorder (ADHD), will gradually increase, endangering their academic performance as well as their physical and mental health (Thomas et al., 2015). Due to the far-reaching effects of these challenges, it is crucial to gain insight into the attentional processes that occur in early development (Atkinson & Braddick, 2012).

The attention network test (ANT) proposed by Fan and colleagues is a classic and broadly acknowledged paradigm for assessing the efficiency of three attention networks (Fan et al., 2002). The ANT and its variants have been extensively applied to examine the developmental

characteristics of attention (Arora et al., 2021). In addition, some other paradigms have been adopted to measure attentional development. For instance, Hrabok et al. (2007) employed the "Help the farmer" task to assess the development of the alert network. Goldberg et al. (2001) adopted the "Covert orienting task" to measure the development of the orient network. The Go/No-Go task (Lewis et al., 2018), Stroop task (Lyon et al., 2022), and Simon task (Tiego et al., 2020) have been used to evaluate the development of the execution control network. The diverse developmental courses of attention identified by various researchers may be attributed to the varied tasks employed in their studies.

Apart from the deviant paradigms for measuring various attentional functions, the majority of studies exhibit a relatively low level of reliability. In the primary study (Fan et al., 2002), the test-retest reliability coefficients for the alerting, orienting, and executive control networks were 0.52, 0.61, and 0.77, respectively, when two sessions were conducted in adults within a single day. MacLeod et al. (2010) analyzed 15 studies conducting the ANT in adults. They revealed that the average split-half reliability for the alerting, orienting, and executive control networks were 0.20, 0.32, and 0.65, respectively. The children version of ANT exhibited even lower levels of reliability. For instance, Ishigami and Klein (2014) uncovered the test-retest reliability for the alerting, orienting, and executive control networks to be 0.16, -0.25, and 0.22, respectively, in children aged between 6 to 8 years. Draheim et al. (2019) argued that the unstable state of subjects, the speed-accuracy trade-off, and the inability to separate a single psychological component from the measurement indicators were the main reasons for the low reliability of reaction time (RT)-based measurement.

As a result of diverse paradigms and low reliabilities, the developmental trajectories of attentional functions are inconsistent across studies. For example, some studies have found that the alerting network attains stability by the age of seven or nine (Abundis-Gutierrez et al., 2014; Rueda et al., 2004), while others argued that it continued to develop into the late childhood or

even into young adulthood (Boen et al., 2021; Posner et al., 2020; Suades-Gonzalez et al., 2017). Similarly, the orienting network and executive control network have been observed to stabilize around the age of six or seven (Lewis et al., 2018; Posner et al., 2020; Suades-Gonzalez et al., 2017). Nevertheless, other research indicated that their development may extend beyond the age of seven (Boen et al., 2021; Federico et al., 2017; Pozuelos et al., 2014). These studies have highlighted the diverse developmental trajectories of attentional functions, particularly during the primary school years.

In the current study, we aimed to assess the developmental trajectories of attentional functions by implementing a measurement paradigm with high validity and reliability. The novel paradigm was adapted from the classic ANT to guarantee its high validity. Furthermore, we adopted the steady-state block design to ensure a high reliability measurement for attentional functions (Gao et al., 2019; Wang et al., 2016). The steady-state block design presented the same experimental condition at a fixed frequency to reduce the fluctuating expectations between trials and avoid the mutual interferences between experimental conditions (Zhang et al., 2023). Therefore, it afforded a stable and predictable environment for the subject to operate in, and could effectively isolate each attentional function and the collaboration among attentional functions (Wang et al., 2015). The non-orthogonal method was further adopted to avoid inter-network interferences. Evidence indicated significant differences in the results obtained through orthogonal and non-orthogonal methods, with the latter proving superior in obtaining single measurements (McConnell & Shore, 2011; Wang et al., 2014). Through these operations, we envisage addressing issues concerning the stability of subject states and the purity of cognitive components that influence the reliability of measurement (Draheim et al., 2019). Overall, we provided a high reliability composite attention test (HR-CAT) and measured with certainty the developmental courses of coordination and interaction among attentional networks beyond the efficiency of each attentional network in primary

school children.

2 METHOD

2.1 Participants

Subjects were recruited from a primary school situated in the urban-rural interface of Sichuan Province, where they were accommodated in residential premises. All children's ethnicity was Han. The research content and potential conflict of interest were fully disclosed to all subjects and their respective guardians. The research protocol was conducted in strict accordance with the Helsinki Ethical Agreement, and informed consent was obtained from both the children and their guardians. All participants were also required to sign a written informed consent form approved by the Ethics Committee of the Institute of Brain and Psychological Sciences, Sichuan Normal University, prior to initiating the experiment.

Data were collected between October 2020 and June 2021. A total of 281 children, comprising 109 girls, participated in the study, with a mean age of 9.48 years, ranging from 5.98 to 13.24 years old. Four children were excluded from further analysis due to their failure to complete the experiment. All participants were right-handed, with normal or corrected to normal vision, and no one was color-blind. Children with prior history of mental retardation, brain trauma, neurological disease, physical impairment, and learning disabilities were excluded.

2.2 Material and procedure

As shown in Figure 1, the task contained eight blocks, each representing one task condition [i.e., alerting (A), baseline (B), executive control (E), orienting (O), alerting and executive control collaboration (AE), alerting and orienting collaboration (AO), executive control and orienting collaboration (EO), and common collaboration (AEO)]. Each block consisted of 24 trials. The overall task lasted for about 15 minutes.

At the onset of each trial, a black line segment appeared at the center of the screen as the fixation point for 1.1 seconds. The line segment had a length of 3 mm and a width of 1 mm. The line segment remained for 0.2 second under B, E, O, and EO conditions, or transition to a red cue for 0.2 second under A, AE, AO, and AEO conditions. The sound of a "click" was combined with the red cue to increase the level of alertness. Afterward, the line segment remained for 0.2 second, forming a fixed cue-target interval. The target, comprising five arrows, was then presented for 1.7 seconds or disappeared upon recording a response. The arrows were presented at the center of the screen, with the third arrow overlapping the line segment, or they were displayed at the top or bottom of the line segment. Each arrow measured 3 mm in length and 2 mm in width, with a combined length of 20 mm for all five arrows. The vertical distance from the fixation was 26 mm when the arrows were presented at the top or bottom of the line segment. At last, a fixation point was presented, ensuring that the entire trial lasted 3.2 seconds.

The program was run on a 14-inch laptop with gray background. The Psychology toolbox embedded in the MATLAB was used for programming, stimulus presentation, and timing control. Before the experiment, each participant completed 24 practice trials to familiarize themselves with the procedure. The experiment was conducted in a dimly lit office, with the subjects seated comfortably and positioned 60 cm away from the screen.

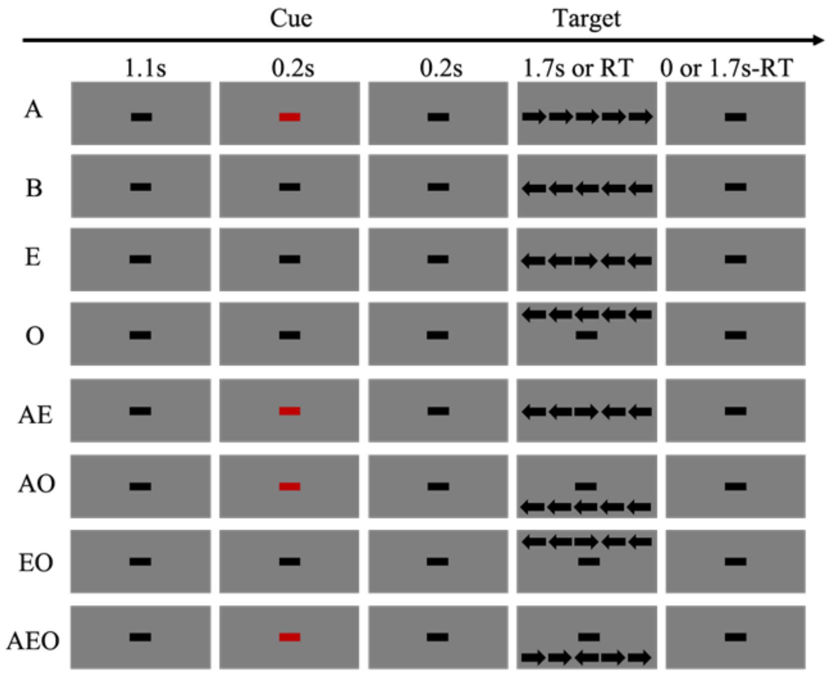

FIGURE 1. Illustration of the highly reliable composite attention test. Each task was conducted trial by trial in an independent block. A: alerting; B: baseline; E: executive control; O: orienting.

2.3 Indicators of attentional networks

The mean and median of RT for all correct trials as well as the accuracy of each condition were calculated. In trials with error responses and trials with RTs exceeding the mean RT plus or minus 2.5 standard deviations (SD), the RTs were replaced with the median RT of that condition. This operation retained all trials and enabled the assessment of split-half reliability, which depended on the random selection of trials. Afterwards, the median RT of each condition was recalculated and utilized to compute the index of attentional networks.

We adopted four potential methods to calculate the indicators of attentional networks and divided these indicators into three categories: the efficiency of single attentional network, the coordination between attentional networks, and the directional influence between attentional networks.

The first method entailed the direct subtraction of two RTs. For instance, the efficiency of a single attentional network was defined by the difference between the RT of this network and

the RT of the baseline condition. The efficiencies of A, E, and O were showed by equations (1)-(3). The RT in each equation represented the mean RT for a given condition of each subject.

$$A = RT_{(A)} - RT_{(B)} \tag{1}$$

$$E = RT_{(E)} - RT_{(B)} \tag{2}$$

$$O = RT_{(O)} - RT_{(B)} \tag{3}$$

Similarly, the coordination between attentional networks was characterized by the difference between the RT of a collaborative condition and the RT of the baseline condition. The efficiencies for the coordination of AE, AO, EO, and AEO were showed by equations (4)-(7).

$$AE = RT_{(AE)} - RT_{(B)} \tag{4}$$

$$AO = RT_{(AO)} - RT_{(B)} \tag{5}$$

$$EO = RT_{(EO)} - RT_{(B)} \tag{6}$$

$$AEO = RT_{(AEO)} - RT_{(B)} \tag{7}$$

Furthermore, the directional influence between attentional networks was defined as the change in the efficiency of the current attentional network when additional attentional networks were introduced. This change was expressed by the difference of RTs between them. The twelve directional influences between attentional networks were showed by equations (8)-(19). The M→N in these equations referred to the directional influence of M on N.

$$A \rightarrow E = RT_{(AE)} - RT_{(E)} \tag{8}$$

$$A \rightarrow O = RT_{(AO)} - RT_{(O)} \tag{9}$$

$$E \rightarrow A = RT_{(AE)} - RT_{(A)} \tag{10}$$

$$E \rightarrow O = RT_{(EO)} - RT_{(O)} \tag{11}$$

$$O \rightarrow A = RT_{(AO)} - RT_{(A)} \tag{12}$$

$$O \rightarrow E = RT_{(EO)} - RT_{(E)} \quad (13)$$

$$AE \rightarrow O = RT_{(AEO)} - RT_{(O)} \quad (14)$$

$$AO \rightarrow E = RT_{(AEO)} - RT_{(E)} \quad (15)$$

$$EO \rightarrow A = RT_{(AEO)} - RT_{(A)} \quad (16)$$

$$O \rightarrow AE = RT_{(AEO)} - RT_{(AE)} \quad (17)$$

$$E \rightarrow AO = RT_{(AEO)} - RT_{(AO)} \quad (18)$$

$$A \rightarrow EO = RT_{(AEO)} - RT_{(EO)} \quad (19)$$

Considering that individuals exhibited varying baseline reaction speeds, we used the ratio score as another method to define the aforementioned efficiencies (Wang et al., 2015). The ratio score was defined as the rate of change of the aforementioned efficiency relative to the baseline or original condition (e.g., A, A→E, and O→AE in equations (20)-(22)).

$$A = \frac{RT_{(A)} - RT_{(B)}}{RT_{(B)}} \quad (20)$$

$$A \rightarrow E = \frac{RT_{(AE)} - RT_{(E)}}{RT_{(E)}} \quad (21)$$

$$O \rightarrow AE = \frac{RT_{(AEO)} - RT_{(AE)}}{RT_{(AE)}} \quad (22)$$

In order to avoid the trade-off between speed and accuracy in traditional RT-based attentional scores, we further adopted the balanced composite score (BIS)(Liesefeld & Janczyk, 2019) to calculate each attentional score. The formula of BIS was showed by equation (23).

$$BIS = Z_{(ACC)} - Z_{(RT)} \quad (23)$$

In this equation, ACC represents the accuracy while RT refers to the median RT of a given condition of each subject. The Z value denotes the location of an individual's score within the distribution of scores for all subjects. A superior BIS equates to greater accuracy and faster RT, thereby indicating a better performance. The BIS could be calculated using the original score or the ratio score obtained in the first two methods. Therefore, we could get four kinds of scores,

namely the original score, the ratio score, the original BIS, and the ratio BIS.

2.4 The reliability of attentional scores

The split-half reliability of the nineteen attentional scores (e.g., in equations (1)-(19)) was evaluated with the Monte Carlo simulation in the MATLAB 2022b Software (MathWorks., U.S.A). Specifically, the 24 trials of each block were randomly divided into two halves 10000 times. The attentional scores were calculated for each of the two halves, respectively. The Pearson's correlation between the two scores was computed across all subjects. The split-half reliability was defined as the mean of 10000 correlation coefficients.

All four kinds of attentional scores, each with 19 items, underwent the reliability analysis. The two (original, ratio) by two (non-BIS, BIS) repeated measures ANOVA and paired-samples T test in the SPSS Statistics Software 25 (IBM., U.S.A) were used to test which method is the best for the calculation of attentional scores. The attentional scores computed by the best method would be used for further analyses.

2.5 The developmental trajectories of attentional functions

The SPSS Statistics Software 25 was used to test the developmental trajectories of attentional functions. Linear and quadratic fittings were conducted, with age as the independent variable and attentional scores as the dependent variable, to investigate whether attentional functions exhibit linear or quadratic trend of development.

2.6 Gender difference during the development of attentional functions

We also tested the gender difference during the development of attentional functions. The data were analyzed with Stata Statistical Software 17 (StataCorp., U.S.A). Attentional scores demonstrating a significant developmental trend were employed as the dependent variables, with age being the independent variable. Gender was set as the group variable (b0: girl group, b1: boy group). The Bootstrap method was used for testing the significance of between-group differences (Cleary, 1999). The null assumption, H_0: $d_0 = 0$, implies that there is no significant

difference in the estimated coefficient values between groups. The empirical *p*-value, obtained through the Bootstrap method, represents the probability of observing the actual coefficient difference between groups. Steps were as follows: (1) Pooling the samples from the boy group and the girl group, assuming that the numbers of people from the two groups were n_1 and n_2, respectively. Then, $N = n_1 + n_2$; (2) In each round of simulation, two groups, one consisting of boys (n_1) and the other of girls (n_2), were randomly selected from the N; (3) The coefficients for each group were determined, and the difference between them (d_i) was calculated; (4) To obtain the empirical *p*-value, which is comparable to the *p*-value in the traditional test, steps 2 and 3 were repeated for k times (k=1000). Afterwards, calculating the percentage of d_i (i=1, 2…, k) which is greater than the actual coefficient difference d_0. If more than 95 % of the d_i were greater than d_0, then the empirical *p*-value was less than 0.05, signifying a gender difference.

Multiple comparisons in the above statistics were corrected at $p < 0.05$ level using the Bonferroni method (Bland & Altman, 1995).

3 RESULTS

The majority of the children (277 out of 281) completed the experiment successfully with the mean accuracy of each condition exceeding 94 % and the median of RT between 535-882 ms (see Table 1).

TABLE 1 The RT and accuracy of eight attentional conditions

Attentional index	RT (ms, median±SD)	Accuracy (%, mean±SD)
A	535.67±100.98	97.41±6.11
B	599.25±114.10	97.78±7.13
O	694.27±126.23	97.28±7.24
E	712.79±138.06	96.83±5.85
AO	639.83±115.66	96.57±5.28
AE	672.77±147.12	95.02±6.96
EO	882.30±170.28	94.75±7.85
AEO	846.92±152.16	94.13±9.23

3.1 Split-half reliability

The ANOVA showed significant main effect of BIS (F (1, 18) =13.91, p=0.002, η^2p =0.45) and ratio (F (1, 18) =21.77, p<0.001, η^2p =0.55). The interaction between BIS and ratio was also significant (F (1, 18) =22.96, p<0.001, η^2p =0.56). Specifically, the original BIS exhibited higher reliability coefficients than the ratio BIS (t (18) = 4.77, p < 0.001, Cohen's d= 1.09), whereas no significant difference was observed between the original score and ratio score (t (18) = 0.74, p = 0.469, Cohen's d = 0.17). Overall, the original BIS method exhibited the highest reliability coefficients in almost all of the scores (see Table 2).

TABLE 2 Split-half reliability of basic attentional functions and their relationships

	Attention index	Original BIS	Ratio BIS	Original score	Ratio score
Attentional efficiency	A	0.87	0.87	0.82	0.81
	E	0.90	0.89	0.84	0.84
	O	0.90	0.89	0.77	0.77
Attentional collaboration	AE	0.91	0.91	0.91	0.91
	AO	0.88	0.88	0.84	0.84
	EO	0.92	0.90	0.80	0.80

	AEO	0.92	0.91	0.90	0.90
Attentional interaction	A→E	0.85	0.84	0.80	0.80
	A→O	0.85	0.84	0.78	0.78
	E→A	0.89	0.87	0.92	0.92
	E→O	0.91	0.90	0.74	0.74
	O→A	0.82	0.81	0.81	0.80
	O→E	0.85	0.83	0.72	0.72
	AE→O	0.91	0.91	0.87	0.87
	AO→E	0.86	0.85	0.85	0.85
	EO→A	0.90	0.87	0.81	0.81
	O→AE	0.87	0.86	0.90	0.90
	E→AO	0.90	0.89	0.90	0.90
	A→EO	0.83	0.83	0.77	0.77

3.2 Developmental trajectories of attentional functions

For the basic attentional functions, only the E score showed a significant non-linear developmental trajectory (R^2=0.056), while the inflection point appeared at the age of 10 (see Fig. 2), suggesting that there is a continuous development of E before the age of 10. The collaboration of EO exhibited a significant non-linear developmental trajectory, which can also be accounted for by the linear trend. The developmental trajectories of the interaction of E→O, E→A, and EO→A can be explained by the linear trend, with the non-linear trend also showing significance. For the quadratic trends of the development of EO, E→O, E→A, and EO→A, the inflection point appeared at the age of 11.6, 11.91, 12.25, and 12.38, respectively. This suggests that their development extends into the higher grades of primary school. The remaining scores did not exhibit either a linear or non-linear trend after the multiple comparison correction.

Since all the aforementioned variables contained the E, we regressed out E from them, and re-performed the fitting analysis. The results showed that only the linear developmental trend was significant, whereas the quadratic development trend dissipated.

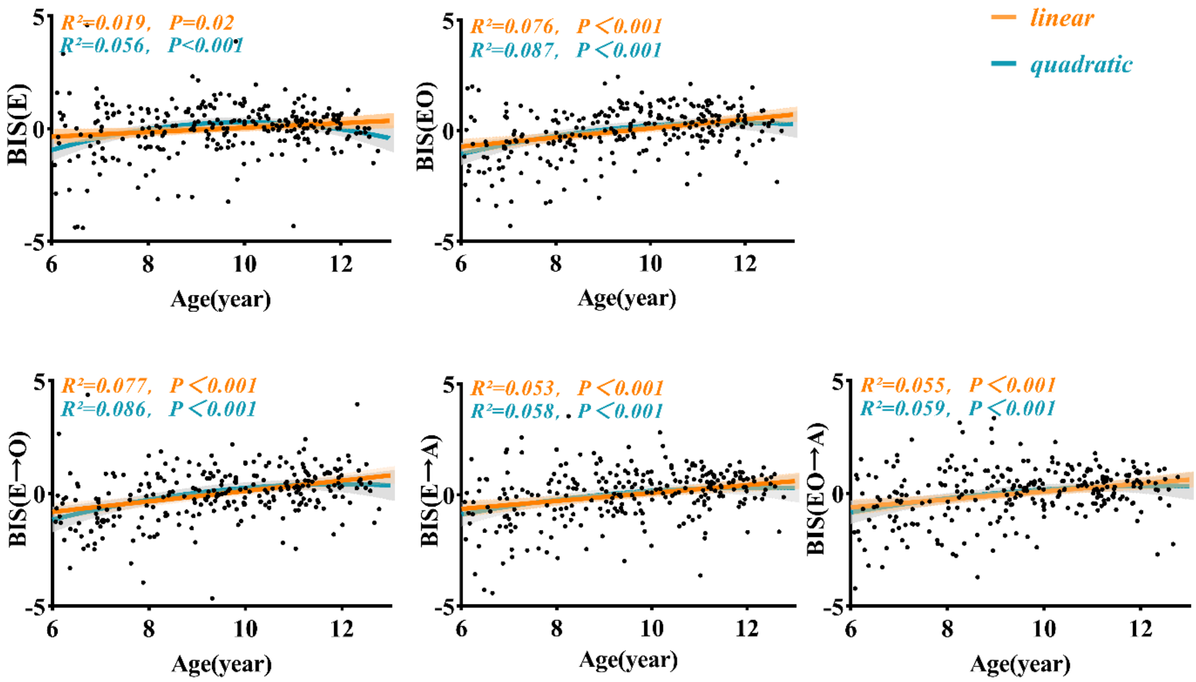

FIGURE 2 The developmental trends of basic attentional functions and attentional collaborations

3.3 Gender differences between attentional functions

The observed improvements in attentional scores with age showed no discernible differences in the developmental trends between boys and girls (see Table 3). However, both boys and girls contributed to the development of EO, E→A, and E→O. Boys had a specific contribution to the development of EO→A. Overall, there was no significant gender difference for the development of attentional functions.

TABLE 3 The gender effect during attentional development

Index	Girl coefficient（b0）	Boy coefficient（b1）	Coefficient difference（b0-b1）
E	0.13	0.08	0.04
EO	0.21**	0.20**	0.01
E→A	0.18**	0.18**	0.01
E→O	0.25*	0.22**	0.02
EO→A	0.15	0.19**	-0.04

* p<0.05, ** p<0.01

4 DISCUSSION

We conducted a highly reliable assessment to the developmental trajectories of basic attentional functions and their collaborations in primary school children. We found that the development of E, EO, E→O, E→A, and EO→A in primary school continue, yet their rate of growth slows after the age of 10, 11.6, 11.91, 12.25, and 12.38, respectively. However, we didn't find a gender difference on the developmental trajectories of all the attentional scores. This study provided trustworthy evidence that during primary school, attentional functions were marked by the development of executive control, its collaboration with orienting, and its impact on the orienting and alerting functions. Of note, it was the initial attempt to evaluate the developmental characteristics of attentional collaborations. Overall, we proposed a mechanism of attentional development that revolved around executive control in primary school.

4.1 The development of basic attentional functions in primary school

For many years, there has been a debate concerning the developmental trajectories of attentional functions. Some researchers concurred that the basic attentional functions in childhood develops gradually with age (Kronenberger et al., 2020; Morandini et al., 2021; Pan et al., 2019). However, some other studies suggested that the development of basic attentional functions reach a plateau around the age of seven or nine, while the continual enhancement of attentional functions in some literatures may be a manifestation of increased reaction speed (Abundis-Gutierrez et al., 2014; Lewis et al., 2018; Posner et al., 2020; Suades-Gonzalez et al., 2017). In line with the latter, our research revealed that alerting and orienting did not experience notable growth between the ages of 6 and 13. In addition to behavioral maturity, the contingent

negative variation (CNV), a typical electroencephalographic indicator of alertness, had been found to reach the adult level by ages 9-10 (Jonkman, 2006). Furthermore, the activation of the putamen, a core brain region for orienting, had achieved the adult level by ages 8-12 (Konrad et al., 2005). In fact, alerting and orienting are the initial functions of attention in infants (Graven & Browne, 2008; Hitzert et al., 2015). The earliest development of alerting and orienting is essential for infants to explore the world.

By contrast, we observed that the executive control still develops in primary school, though its rate of development slows down. This may signify that the development of executive control has distinct stages. Late childhood signals the termination of the prior stage, whereas the subsequent stage may not initiate until adolescence. This assumption is in line with the "readiness for change" model which suggests a two-stage development of cognitive control during childhood and adolescence (Crone & Steinbeis, 2017). It can also reconcile the inconsistent results that executive control achieves stability at primary school in some studies, while it continues to develop until young adulthood in other studies (Aubry & Bourdin, 2021; Boen et al., 2021; Lewis et al., 2018; Posner et al., 2020; Suades-González et al., 2017). An alternative interpretation is that the executive control includes two components: conflict resolution and inhibition control. It has been suggested that, after the age of 7 years old, the ability to conflict resolution has entered a plateau (Posner et al., 2020), but children exhibit gains in inhibitory control with the development of age (Zhou et al., 2022). The Flanker is more indicative of conflict resolution, possibly contributing to the slowdown in the development of executive control in later childhood. If so, some other tasks, such as the stop-signal task, which

are more indicative of inhibition control, may reveal different trends. Both of these assumptions require further verification.

4.2 The development of attentional collaborations in primary school

Theoretically, the successful operation of each attention network relies on the cooperation of other networks. For instance, alerting depends on bottom-up stimulus induction (i.e., the phasic alerting) and top-down autonomic maintenance (e.g., the tonic alerting), so it needs the cooperative participation of orientation and executive control (Sarter et al., 2001). Orienting depends on a certain level of alerting, stimulus selection, and eye movement control, so alerting and executive control are integral to this process (Hendry et al., 2019). Executive control necessitates one to orienting and maintenance on target stimuli, thus requiring orienting and alerting (Bast et al., 2018). Esterman and Rothlein (2019) have proposed that sustained attention is a result of the combined efforts of staying alert for a long duration, having autonomous control to suppress distractions, and having a constant orientation. Therefore, collaboration between different attention networks is a necessity for successful attentional functions, as well as a significant theoretical issue. Moore (2016) put forward an idea that the development of complex systems results from the interaction of a number of factors or processes. Within this framework, complex attentional functions are only apparent when the basic attentional functions reach a certain level and are able to collaborate effectively.

In primary school, alerting and orienting are gradually stabilizing, while executive control is continuously evolving at a high level (Lewis et al., 2017). Therefore, the development of attentional collaboration may be the main objective at this stage. In line with this, we observed

a significant enhancement of the executive control-orienting collaboration. Posner and Rothbart (2000) also stressed the parallel development of orienting and executive attention networks and suggested that the orienting may represent a rudimentary form of inhibition. Some researchers have pointed out that the coordination of top-down executive attention and bottom-up attention orienting is the neural mechanism underlying these two cognitive processes (Tian et al., 2014). Exogenous orienting is a bottom-up process that occurs when salient stimuli or changes in the environment draw and direct attention automatically (i.e., stimulus-driven). However, the orienting of attention towards a distracting event may impair current ongoing processes. In order to avoid permanent distraction in an ever-changing environment, the attention based on expectancies or internal goals, which is referred to as endogenous or top-down orientation, is essential to ensure goal-directed behavior (Moyano et al., 2022; Wetzel & Schröger, 2007). These mechanisms are known to be mostly dependent on executive attention (Rothbart et al., 2011), which shares common neural substrates with endogenous orienting (Rueda et al., 2015). Therefore, the development of endogenous orientation inevitably depends on the development of executive control. Wainwright and Bryson (2005) examined the development of endogenous orienting in 6-, 10-, and 14-year-old children and adults using the Posner's visual orienting task. They suggested that the better performance of older children could be understood as better executive control helping to modulate the breadth and density of attentional focus. Sørensen et al. (2019) further suggested that cardiac vagal activity (CVA), a specific psychophysiological indicator of executive control, is associated with the early-stage of attentional orienting. Their results showed that high levels

of CVA were modulated by the interaction between intrinsic orienting and executive control. Pozuelos et al. (2014) also observed significant interactions between orientation and executive control in the ANT of children aged 6-12 years, with this trend continued to develop over this period. Accordingly, the enhanced collaboration of executive control and orienting may indicate a more complex system that can coordinate top-down and bottom-up information more effectively.

Furthermore, it has been suggested that the attentional disengagement component of orientation is influenced by the inhibitory control component of executive control. The stronger the inhibitory control capability, the faster the attentional detachment (Hitzert et al., 2014), that is, the rapid development of inhibitory control promotes the disengagement and reorientation of attention. Sørensen et al. (2019) argued that a higher CVA may facilitate the flexible uptake of valid information during goal-oriented behavior, while concurrently preserving attention on task-specific stimuli in the presence of distracting cues. In sum, a higher level of executive control can have a beneficial effect on orientation.

The effects of executive control, in conjunction with orienting, on alerting, also increased with age. Our findings are highly repeatable, yet these phenomena are the initial discoveries and there is a lack of theoretical explanations to them. The theoretical interdependence of attention networks may contribute to the effect of the collaboration of executive control and orientation on the alerting. Furthermore, studies on sustained attention have provided limited but valuable evidence on the effect of executive control on alerting. For instance, Luna et al. (2022) have found that the decrease in the executive component of vigilance was moderated

by changes in executive control across time-on-task. This may explain why the execution control has not been found to have an effect on alertness in the traditional ANT with event-related design. In addition, in the traditional ANT, the execution control is always conducted after alertness, which makes it impossible to identify the effect of later events on earlier ones. In the current study, participants persistently perform the same task over a period of time, thus allowing us to detect the influence of control execution on alertness similar to that in sustained attention tasks.

In addition to these findings, regression analysis showed that when excluding the influence of E, the linear developmental trajectory of attentional collaborations remained. This indicates that the developmental patterns between basic attentional functions and their collaborations are somewhat different.

4.3 Gender difference

The gender difference in the field of cognitive development has attracted considerable interest (Bethlehem et al., 2022). The absence of gender influence on the tendency of attentional development aligns with the views of some scholars but not others (Grissom & Reyes, 2019; Panwar, 2021; Slot & von Suchodoletz, 2018). For instance, utilizing the ANT, a longitudinal study explored differences in attentional development between children with ADHD and typically developing children. The study revealed that gender and ADHD symptoms interacted with age on executive attentional performance. Notably, girls with ADHD demonstrated superior performance and exhibited greater advancements over time (Suades-Gonzalez et al., 2017). Another study utilizing the ANT with normal participants found no

significant gender difference in alertness and executive control, but did reveal significant gender difference in orientation (Liu et al., 2013). However, an earlier study has indicated that there is no disparity in orientation between males and females (Koshino et al., 2000). It is possible that orientation involves multiple operations such as disengage, switch, and engage (Posner & Petersen, 1990; Posner & Raichle, 1994), but we and other researchers did not decompose the orientation to measure it like the ANT-R (Fan et al., 2009). In addition, varying the stimulus onset asynchronies (SOAs) between cues and targets will also influence the orientation (Mullane et al., 2016). The discrepant results among studies may stem from the measurement of different types of orienting. However, in combination with the above findings, sex differences are often triggered by other factors, such as motivation level (Dye & Bavelier, 2010) and cultural differences (Sobeh & Spijkers, 2012). The exploration of gender differences during attentional development remains necessary.

4.4 Paradigm & reliability

We used the techniques of steady-state block design, non-orthogonal computation, and directional interaction to improve the validity and reliability of the classic ANT. Based on the HR-CAT, we determined that the split-half reliability of the test for primary school children reached approximately 0.8, demonstrating a substantial increase compared to the previous research on children, which only achieved a reliability of about 0.2 (Ishigami & Klein, 2014). This suggests that the HR-CAT has the potential to advance research on attention in children as well as in individuals with abnormal attention patterns.

5 LIMITATION

Future research will benefit from solving some limitations of the present study. First, we did not control intra-individual differences across time. A longitudinal design is needed to overcome this limitation, wherein a cohort of children undergoes the HR-CAT at multiple time points. Second, we did not include older children, adolescents, and adults. This has to be kept in mind because our results do not offer any information regarding the development trajectory of attention networks beyond the age of 13. At the same time, the study included both urban and rural subjects, but did not collect data on household economics. Although the split-half reliability in this work reached around 0.8, it is still limited by sample sources and other potential factors. The current findings warrant further studies with a wider sampling environment and a larger sample size.

6 CONCLUSION

This study provided a highly reliable paradigm to measure the developmental trajectories of attention in primary school children. It broadened the scope of attentional development by proposing the collaboration and directional influence between attentional functions. The developments of basic attentions and their collaborations, despite revolving around executive control, are driven by relatively independent mechanisms.

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